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Highly efficient fluorescence sensing with hollow core photonic crystal fibers

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Abstract: We investigate hollow core photonic crystal fibers for ultra-sensitive fluorescence detection by selectively infiltrating the central hole with fluorophores. Dye concentrations down to 10^{-9} M can be detected using only nanoliter sample volumes.

1. Introduction

In recent years the research interest in microstructured optical fibers (MOFs) has rapidly increased. Due to their special optical properties, which result from the incorporation of holey structures into the fiber profile, MOFs have been widely used in the field of telecommunication, non-linear optics and, in particular, chemical and biological sensing [1, 2]. A promising feature of MOFs for various sensing applications is the possibility to infiltrate sample material into the holes, where it can interact efficiently with the guided light. This interaction is of evanescent nature for solid core MOFs, since light is index-guided within the higher dielectric and only a small part of the field energy penetrates into the sample volume. Hollow core photonic crystal fibers (HCPCFs) [3, 4], a special class of MOFs whose guiding mechanism is based on the photonic bandgap effect, avoid this drawback. In HCPCFs light is guided within the central hole, which is surrounded by smaller cladding holes that provide the bandgap confinement. Consequently, a much higher interaction cross section of the field energy and the sample material can be achieved. In this way sensing devices for gases [5] as well as for liquids [6] have been implemented. The fundamental difference between both types of sample material is that gases in general do not influence the bandgap guiding (due to their low refractive index), while liquids change the guiding mechanism to index guiding when selectively injected into the hollow core [7]. Here we investigate the fluorescence emission from HCPCF in both regimes by either coating the fiber core with fluorophores or infiltrating doped solutions into the core [8,9]. The influence of reabsorption effects and intermolecular interactions on the fluorescence signal is studied. We show that in both cases dye concentrations below 10^{-9} M can be detected using only nanoliter sample volume, thus demonstrating the attractiveness of HCPCFs for various sensing applications.

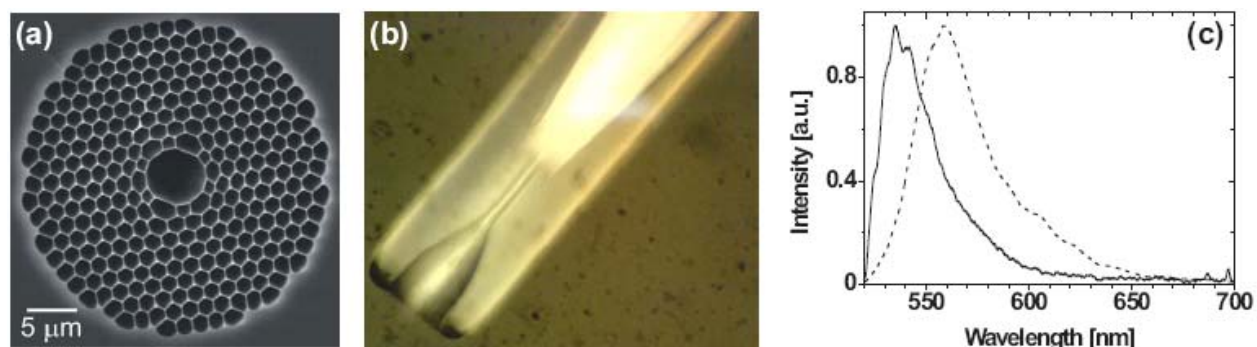


Fig. 1. (a) Electron microscope image of a HCPCF and (b) side view of the fiber after sealing the outer holes using a fusion splicer. (c) Fluorescence spectrum of R6G (concentration 10^{-9} M) in a HCPCF (solid line) and spin-coated on glass (dashed line).

2. Experiment and Results

We use two different types of HCPCFs for our measurements. For coating the hollow core and operation in air a HCPCF designed for a central wavelength of 510 nm is used (Fig. 1a). On the other hand, a HCPCF designed for a central wavelength of 1550 nm, is infiltrated with liquid. In both cases the fiber preparation contains several steps since only the central hole needs to be coated or infiltrated. For this purpose a fusion splicer technique [10, 11] is used to selectively seal the cladding holes at both end facets while the central hole remains open (Fig. 1b). The fiber is then filled with a dye-doped solution using only capillary forces. For coating purposes the solvent is evaporated afterwards.

We have measured the fluorescence of several fluorophores within the fiber core and were able to demonstrate that concentrations down to 10^{-9} M can be detected for both guiding mechanisms (Fig. 1c). The overlap of the emitters with the excitation light is experimentally determined and in excellent agreement with theoretical simulations. We find that the detection efficiency for the liquid core is superior to the that of the coated core due to the larger field overlap. Moreover, we investigate the influence of reabsorption effects and the intermolecular interaction of the fluorophores. As a result, we find that both effects are negligible for concentrations below 10^{-7} M. Furthermore, we successfully tested the reusability of the selectively filled HCPCFs by refilling the core with different solutions.

3. Conclusions

In conclusion, the selective coating technique as well as the selective infiltration of liquids into the HCPCF core have proofed to be suitable for various sensing applications. Coated fibers may be used in gas sensing devices where the fluorescence signal is affected by the concentration of several gases. Furthermore, surface-enhanced Raman scattering [12] can be established as well if metal particles are infiltrated. Furthermore, by functionalization of the core walls and infiltration of biochemical samples, various chemical reaction or biological processes might be monitored. Due to the small sample volumes integration in optoelectronic devices could be managed [13]. Concepts to use the strongly confined light also for particle manipulation are attractive as well [14].

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